Observing SO_2 emissions at Japanese volcanoes using an ultraviolet imaging camera

Thomas Bouquet[1]*, Kisei Kinoshita[2], Matthew Watson[3]

[1]*Faculty of Science, Kagoshima University, 1-21-35 Korimoto, Kagoshima, 890-0065, Japan*

[2]*Faculty of Education, Kagoshima University, 1-20-6 Korimoto, Kagoshima, 890-0065, Japan*

[3]*Department of Earth Sciences, University of Bristol, Queen's Road, Bristol, BS2 9RQ, UK*

**t.bouquet@ms.kagoshima-u.ac.jp*

Abstract

A newly developed ultraviolet (UV) imaging camera offers a new approach to the ground-based surveillance of volcanic sulphur dioxide (SO_2). Using highly sensitive 2-dimensional CCD technology and a bandpass filter centred in the UV region where SO_2 selectively absorbs UV light, the camera is able to quantify SO_2 within a gas plume in great detail. This study presents results from Sakurajima and Satsuma-Iojima volcanoes, where image sequences were obtained at an unprecedented temporal resolution and revealed interesting variations in SO_2 emission rate. The SO_2 retrieval technique is also discussed with respect to atmospheric scattering and the use of different UV wavelength filters.

Keywords: gas monitoring, sulphur dioxide, UV camera, Sakurajima, Satsuma-Iojima

1. Introduction

The measurement of volcanic gas emissions is an ongoing objective of volcano hazard monitoring. Of the most abundant gases, sulphur dioxide (SO_2) has been mainly measured remotely: firstly for its high concentration in contrast to low atmospheric levels, and secondly for its specific absorption in the ultraviolet (UV) spectrum (300-315 nm). Utilising this characteristic, the correlation spectrometer (COSPEC) has been in use since the 1970s,[1)] but has been replaced more recently by low-cost and lightweight miniature UV spectrometers, adopting the differential absorption (DOAS) technique.[2)] Both instruments traverse or pan a gas plume and scale UV absorption to SO_2 concentration in accordance with the Beer-Lambert Law. However, calculations of emission rates are often dependent upon crude estimations of plume geometry and wind speed. An unrepresentative wind speed can contribute up to 40% of the overall error,[1)] whilst the time resolution is limited to the duration of individual measurements.

The UV camera therefore offers an improved alternative, adopting the same principles of remote sensing, but also making use of 2-dimensional CCD technology.[3),4)] A synoptic view of a whole gas plume is provided, as well as benefiting from the portability and low detection limit of ground-based technology. A sequence of digitised images allows for improved measurement of plume geometry and velocity, and the delay between individual images can be set to as little as one second thus offering an unprecedented frequency for gas monitoring. This study uses the camera described in 3) and presents the latest images obtained from fieldwork during April 2008, concentrating on results retrieved at Sakurajima and Satsuma-Iojima volcanoes in southern Japan.

2. Methods

2.1. Instrumentation

Instrumentation consists of an Apogee Instruments E6 Alta digital camera with a Kodak KAF-1001E-2 1024×1024 CCD array with 16-bit quantisation level per pixel, a 105 mm lens from Coastal Optics, and a bandpass filter from Andover Optics centred at 307 nm with a 12 nm full width at half maximum. The system is cooled with a thermoelectric cooler and is controlled by the imaging software MaxIm DL (Diffraction Ltd.). In the field the camera is mounted on a standard tripod (fig. 1) and takes around 10 minutes to set up, allowing time for manual adjustment of focus and exposure time. The lens is used with an F number of 4.5, producing a field-of-view (FOV) of approximately 13°.

Fig. 1: Field set-up of UV camera and components.

2.2. SO_2 retrieval

Using sunlight as the source of UV light, the apparent absorbance (A) of SO_2 in plume images at i-th row and j-th column pixel is calculated as follows:

$$A(i,j) = log_{10} [I_o(i,j)/I(i,j)] \quad (1)$$

where I_o = light intensity before passing through SO_2 (background sky), and I = light intensity after passing through SO_2. The plume absorbances are then scaled using measured absorbance values from two calibration cells composed of 115 and 270 ppm.m, to derive the SO_2 slant column concentration. Essentially a "map" of SO_2 column concentration is created and cross-sectional plume profiles can then be extracted to compute SO_2 emission rate.

2.3. Field measurements at volcanoes

The data discussed in this study are based on results from the UV camera deployment at Sakurajima on April 24, 2008, and at Satsuma-Iojima on April 26, 2008. On both occasions a clear blue sky provided a background for measurements (see discussion for specific conditions) and the wind speed was 14.4 ms^{-1} and 8.1 ms^{-1} respectively, calculated from the time difference between integrated vertical SO_2 column profile amounts for the 700th and 900th pixels.

Sakurajima is one of the most active volcanoes in Japan and at the time of imaging, activity consisted of high SO_2 flux (exceeding 1000 tonnes/day (td^{-1}); K. Yamamoto, pers. comm.) and intermittent explosions. A sequence of images was obtained between 15:41 and 16:02 local time at a distance of 4.5 km south-west from the vent, resulting in a pixel resolution of 1.51 m. One image was collected every 5 seconds with an exposure time of 0.6 seconds for each.

In contrast, Satsuma-Iojima is characterised by intensive degassing (SO_2 flux is typically 300-1100 td^{-1}), but no historical eruptions have been recorded.[5] Images were obtained every 5 seconds between 13:31 and 13:43, with an exposure time of 0.8 seconds. The imaging location was 3.15 km WSW from the vent, resulting in a pixel resolution of 0.85 m.

3. Results

Fig. 2 depicts a typical image of SO_2 column concentration, taken at Sakurajima volcano and processed to show heterogeneities within the plume. The plume was moving across the image from left to right, and gas emissions from two craters can distinguished: the first, from Minami-dake to the left of the image, and the second rising from the Showa crater behind the flank in the centre of the image. This is even more apparent when analysing sequential images as one is able to track individual gas "puffs" or pulses in SO_2 emission. Similar features, albeit less dramatic, were also observed at Satsuma-Iojima.

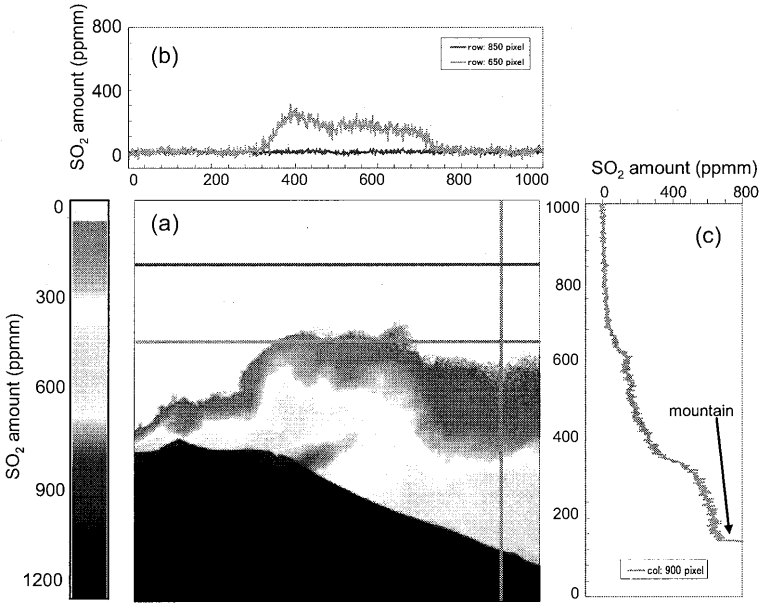

Fig. 2: (a) False-colour image of SO_2 column concentration for a Sakurajima plume at 15:47:58. The scale on the left is of calibrated SO_2 column concentration in ppm.m. (b) Horizontal profiles of the SO_2 column amount at the 850th (dark line) and 650th (light grey line) row pixels. (c) Vertical SO_2 column amount at the 900th (light grey line) column pixels.

SO_2 emission rate was calculated for both volcanoes using integrated vertical SO_2 column profile amounts extracted from the 900th pixel location, multiplied by the pixel resolution and computed wind speed. An angular correction is also applied to account for the deviation from a horizontal plane in the camera's FOV. From each image sequence, average SO_2 flux was approximately 1090 td^{-1} (12.6 kgs^{-1}) and 96 td^{-1} (1.1 kgs^{-1}) for Sakurajima and Satsuma-Iojima, respectively. Temporal variation of SO_2 flux also greatly differs for the two volcanoes (fig. 3): although for Satsuma-Iojima flux remains constant at about 1 kgs^{-1}, the emission rate at Sakurajima ranged from around 10 kgs^{-1} to 18 kgs^{-1}. Peaks in flux can be related to gas "puffs" and two small explosions were observed (indicated in fig. 3), which occur after 392 seconds and towards the end of the sequence after 1070 seconds.

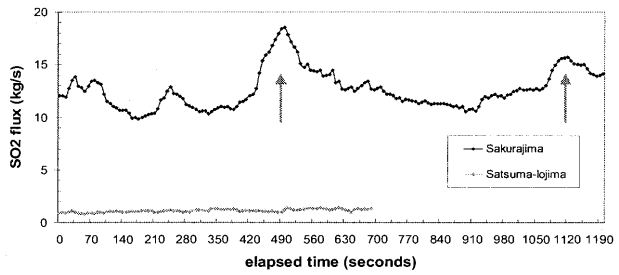

Fig. 3: Temporal variations of SO_2 flux for Sakurajima (dark) and Satsuma-Iojima (light grey) obtained from integrated vertical profiles of the 900th pixel. Arrows indicate peaks caused by explosions.

4. Discussion

4.1. Imaging conditions

Flux calculations derived from Sakurajima imagery appear to agree with regular UV spectrometer (DOAS) measurements (K. Yamamoto, pers. comm.). However, due to recent explosive activity there was a high amount of volcanic ash particles in the air and it is possible that this may influence the SO_2 absorbance signal. Ash particles block UV light, thus indicating artificially enhanced absorbances,[6] but as wind speed was sufficiently high (14.4 ms^{-1}) to transport explosion clouds away during 24 April, it is suspected that ash did not linger above the vent as in other cases. Further investigation using images from other imaging days is necessary to analyse this phenomenon.

No such difficulty exists at Satsuma-Iojima, but clearly camera SO_2 flux values underestimate emission rate by at least a third compared to typical measurements.[5] One reason may be that the whole gas plume was not imaged as it was partially transported behind the flank of the volcano. A second may be due to increased atmospheric turbidity during 26 April, as aerosol scattering between the camera and target would have diluted the SO_2 signal. This was a major issue during the field campaign as such conditions are characteristic of spring in southern Japan. The problem can be modelled by simple atmospheric modelling, whereby signal degradation is dependant upon distance and relative humidity.[7] With this in mind, the camera was deployed at a power station in the UK and images were obtained from successive distances up to 5.3km away from the plume and a clear decrease in absorbance was established (fig. 4).[8] Subsequent extrapolation to a true "zero-distance" value can then be performed, thus providing a simple atmospheric correction for absorbance values. Attenuation factors derived from this method (36%) show reasonable agreement with other studies, approximating 35-50% for short wavelengths (309 nm and 313 nm) over a distance of 2.6 km.[9]

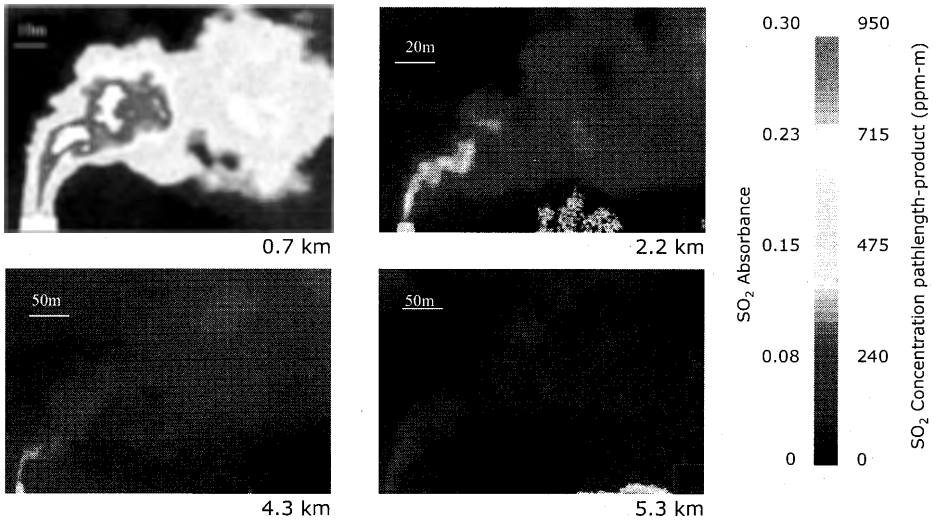

Fig. 4: False-colour power station SO_2 plume images, showing SO_2 absorbance degradation with distance.

4.2. UV bandpass filters

This research was conducted using only a single bandpass filter centred at 307 nm. Ideally the camera system should incorporate a second filter outside the SO_2 absorption signature (i.e. >315 nm), as the difference in transmittance between two filters would increase sensitivity to the SO_2 signal and help to eliminate interference from other gas species.[4] However, with the current system set-up it is difficult to capture an image with two filters as the target plume is constantly moving. In the absence of a secondary imaging system, future study will incorporate the use of a filter wheel enabling quick changes between bandpass filters of different wavelengths. In addition, it is also hoped that filters with a narrower band wavelength will be available to further improve the SO_2 retrieval routine.

5. Conclusion

A UV imaging camera was deployed at Sakurajima volcano and for the first time at Satsuma-Iojima volcano. SO_2 flux was successfully calculated for Sakurajima, averaging 12.6 kgs^{-1} for the 20-minute sequence, and also showed interesting temporal variability due to pulses in gas emissions or explosions. SO_2 flux at Satsuma-Iojima, however, was greatly underestimated due to atmospheric scattering between the camera and target, diluting the SO_2 absorbance signal. It is also expected that use of a single bandpass filter rather than two limits the accuracy of SO_2 detection. In conclusion, it is hoped that, with further development and increased automation, the UV imaging camera could become a useful tool in the remote sensing of gas emissions.

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